

# Continuously Regenerable Freeze-Out CO<sub>2</sub> Control Technology

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## ABSTRACT

Carbon dioxide (CO<sub>2</sub>) removal technology development for portable life support systems (PLSS) has traditionally concentrated in the areas of solid and liquid chemical sorbents and semi-permeable membranes. Most of these systems are too heavy in gravity environments, require prohibitive amounts of consumables for operation on long term planetary missions, or are inoperable on the surface of Mars due to the presence of a CO<sub>2</sub> atmosphere. This paper describes the effort performed to mature an innovative CO<sub>2</sub> removal technology that meets NASA's planetary mission needs while adhering to the important guiding principles of simplicity, reliability, and operability.

A breadboard cryogenic carbon dioxide scrubber for an ejector-based cryogenic PLSS was developed, designed, and tested. The scrubber freezes CO<sub>2</sub> and other trace contaminants out of expired ventilation loop gas using cooling available from a liquid oxygen (LOX) based PLSS. The device was designed for continuous regeneration, with solid CO<sub>2</sub> being removed from the cold freeze-out surfaces, then sublimated and vented overboard. Continuous regeneration allows indefinite scrubber duration for as long as LOX is available from the PLSS.

Simplicity, reliability, and operability are universally important criteria for critical hardware on long duration Lunar or Mars missions. The cryogenic scrubber breadboard has no moving parts, requires no additional consumables, and uses no electrical power, contributing to its simplicity and reliability. It is easy to use; no operator action is required to prepare, use, or shut down the cryogenic scrubber, and it does not require charging or specific regeneration periods. The versatility of the concept allows for operation on Earth, the moon, and Mars.

A conceptual design suitable for a PLSS was developed based on the results of the cryogenic scrubber breadboard testing.

## INTRODUCTION

Oceaneering Space Systems (OSS) and its teammate Raven Aerospace Technology developed and tested an innovative advanced Carbon Dioxide (CO<sub>2</sub>) removal technology based on freezing CO<sub>2</sub> out of a space suit ventilation loop. The purpose of this project was to investigate and advance the knowledge of a low Technology Readiness Level (TRL) CO<sub>2</sub> removal concept for a space suit life support system that has the potential for improvements over current technology.

This effort built on previous work performed by OSS that proved the feasibility of CO<sub>2</sub> freeze out. To determine the basic functionality of the concept, alternate cooling sources to Liquid OXygen (LOX), and potential CO<sub>2</sub> separation, collection, and removal techniques were first considered. LOX was determined to be the only realistic heat sink when considering mass and complexity. Separation, collection, and removal techniques were organized into three categories for further assessment:

1. Single-bed, store CO<sub>2</sub> during EVA, regenerate after EVA
2. Multiple-beds with periodic changeover for regeneration
3. Single-bed with continuous regeneration

Previous work provided a legacy design for the first category, a single-bed, store for Extravehicular Activity (EVA) duration type system. This work, completed in 2002, demonstrated storing four hour's worth of CO<sub>2</sub> in a chilled metal matrix and regenerating it after the four hours of scrubbing. Following this path again would result in improvements, but because it would start at a

medium TRL, it would not achieve the intent of developing a low TRL concept.

Numerous examples of the second category, multiple cycling beds, have been developed including the two-bed Rapid Cycle Amine for a Portable Life Support System (PLSS), and the two-bed molecular sieve system for Skylab. Applying the freeze out technology to a multiple-bed type system was carefully considered, but it was unlikely to provide dramatic improvements over existing technology and would carry similar penalties for moving parts, active control systems, and power.

To our knowledge the third system, a single-bed CO<sub>2</sub> scrubber with continuous regeneration, has not been developed. This type of scrubber would combine the best of the other two categories; virtually unlimited duration, no operator effort, no moving parts, no control systems, and no power requirement.

In the final assessment of these three scrubber categories, it was apparent that pursuing any of them would mature the technology in terms of modeling and verification, testing in a relevant environment, and the physical operation. However, the single-bed, continuous regeneration concept would examine a relatively unexplored area of ventilation loop CO<sub>2</sub> removal and provide the potential for dramatic improvements over existing, higher TRL technologies. This became the project's focus.

A continuously scrubbing and regenerating CO<sub>2</sub> freeze out device is applicable to a LOX-based PLSS with an ejector for ventilation loop flow. The advantages of such a scrubber are that it is extremely simple; it has no moving parts, no mission or lifetime duration limits, no recharge requirements, no power requirements, and no specific actions are required for operation. The fully developed device would have a competitive mass and volume.

## Objectives and Philosophy

The OSS team's philosophy to achieve the project goals was to explore a wide variety of concepts and then converge on a CO<sub>2</sub> removal concept by focusing on meeting requirements and maximizing technical development/return while adhering to the guiding principle of simplicity, reliability, and operability.

The goal of this project was to research and develop an innovative, low TRL, regenerable freeze out CO<sub>2</sub> control technology.

Specific objectives of the project included:

- Develop a breadboard scrubber to TRL 4 or 5

Present a conceptual design that meets the performance parameters and goals shown in Figure 1

Analyze impacts and benefits of the technology  
Make recommendations to further develop and mature the technology for NASA's exploration objectives

Operational Environment	
Vent Loop Flow Rate	6.8 m <sup>3</sup> /hr (4 acfm) with hemispherical helmet <sup>1</sup>
EVA Duration	8 hrs
Metabolic CO <sub>2</sub> Production	25 mg/s nominal (8-50 range)
Operating Pressure	29.6 kPa (4.3 psia)
Performance Goals	
Helmet Inlet ppCO <sub>2</sub>	1 kPa at <469W, 1.3 kPa at <586 W, 2 kPa at <732W
Helmet Inlet Temperature	278 - 305 K (4.4C to 32.2C) <sup>2</sup>
System Volume	<0.015 m <sup>3</sup>
System Power	<50 W
Vent Loop Pressure Drop	<0.125 kPa
Numbers taken from SOW, unless otherwise noted	
Note 1: from OSS PLSS Schematic Study	
Note 2: from EVA Constellation Space Suit Performance and Design Criteria Document, as of 3/24/06	

Figure 1: Performance Parameters and Goals

## APPROACH

The OSS team used the following approach to develop the cryogenic scrubber.

## GROUND RULES AND ASSUMPTIONS

The following assumptions and ground rules were developed to help guide and bound the project.

### Assumptions:

Constant venting to ambient environment is permitted (i.e. ejector system). *Rationale: All PLSS's will vent some amount, so preventing any environmental contamination is unlikely.*  
CO<sub>2</sub> will not be recovered during EVA. *Rationale: Storing CO2 will limit EVA duration, and CO2 is not a valuable resource in the Mars operational environment.*

### Ground Rules for Project and Testing:

Nominal metabolic rate is 300 W.  
The four-hour, 300 Watt (W) average metabolic profile is applicable.  
Nominal suit pressure is 29.6 kilopascals (kPa) (4.3 pounds per square inch absolute (psia)).  
Hemispherical helmet requires a nominal washout flow rate of 113 actual lpm (4 absolute cubic feet per minute (acfm)) (or 32.3 standard liters per minute (slpm) at 29.6 kPa).  
A reasonable average ventilation rate based on ejector gas consumption is 4.7 slpm. *Rationale: A documented ejector design requires ~0.74 lb/hr of O2 for operation at 3.75 psia.*  
Nominal EVA duration is 8 hours.

Humidity is removed before ventilation loop gas enters the CO<sub>2</sub> removal system.

Testing will be done in a sub-atmospheric ventilation loop [101.3 kPa (14.7 psia) ambient, 29.6 kPa (4.3 psia) ventilation loop].

Nitrogen (N<sub>2</sub>) and CO<sub>2</sub> mixture will be used in ventilation loop.

Testing will investigate normal use, start up, standby, off nominal situations (cryogenic interruption).

PLSS schematics and applicability of cryogenic scrubber will be reviewed.

#### Ground Rules for Hardware:

- A single bed, store CO<sub>2</sub> for EVA duration, removal system will not be considered.
- A continuously regenerable system is desirable.
- Moving parts in the low temperature areas are very undesirable.
- Mass is less than 5 kg.

#### LITERATURE INVESTIGATION AND DATA GATHERING

A literature search was conducted and methods of freezing, separating, and storing CO<sub>2</sub> were investigated. Snow and dry ice manufacturing techniques were reviewed. Commercial trace contaminant freeze out systems were investigated for applicability. Alternate cooling sources such as cryocoolers and thermoelectrics were analyzed and deemed unacceptable due to large power and additional PLSS cooling requirements. The literature search also focused on physically removing frozen CO<sub>2</sub> from the ventilation loop. Dust removal techniques, including inertial separators, fabric collectors, and electrostatic precipitators, were examined and documented as potential concepts for frozen CO<sub>2</sub> removal and separation.

The next step in our approach was to create and document different ideas for a cryogenic CO<sub>2</sub> scrubber. The primary functions of the scrubber were determined to be CO<sub>2</sub> capture/separation, bed regeneration and CO<sub>2</sub> processing. Each has several basic categories of solutions (see Figure 2). A continuous regeneration and continuous venting concept provides the most advantages to a PLSS.

Figure 2: Primary Functions and Solution Categories

A brainstorming session was conducted to develop methods for CO<sub>2</sub> freeze out (e.g., on various cold surfaces, in gas stream), CO<sub>2</sub> snow removal (e.g., air knife, vibrating motor, thumper), and CO<sub>2</sub> ejection (e.g., pressure/temperature swing, momentum flow, cyclone separation of snow from gas). These methods were evaluated with respect to applicability and feasibility, resulting in a smaller set of methods that could be analyzed or tested for further down selection.

#### EXPERIMENTAL FEASIBILITY STUDIES AND TESTING

The focus of the experimental feasibility studies was to use simple prototypes to verify the test setup, examine surface area effects on CO<sub>2</sub> freeze out, and characterize the frozen CO<sub>2</sub> structure. Testing was performed in the OSS Cryogenics Laboratory, at 5 to 10 kPa over ambient pressure. The set up included numerous sensors to measure relative humidity, temperature, pressure, flow rate, and CO<sub>2</sub> percentage at various points in the ventilation loop.

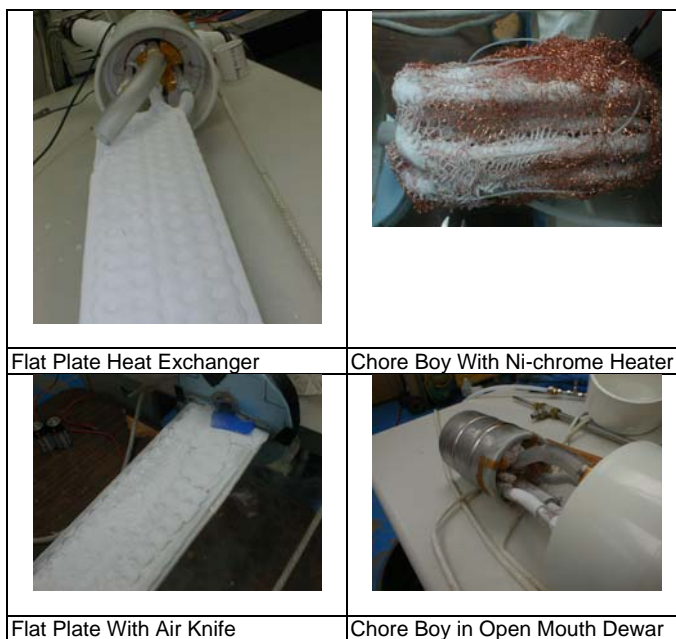


Figure 3: Experimental Feasibility Testing

CO <sub>2</sub> Capture / Separation	Bed Regeneration	CO <sub>2</sub> Processing
Freeze Out	Post-EVA Processing – not considered (explored in previous effort)	Store for Duration – not considered (explored in previous effort)
	Cyclic Regeneration – less desirable due to power/LOX for freeze/thaw cycles	Cyclic Venting – less desirable due to complex valves/moving parts
	Continuous Regeneration – desirable due to minimal LOX and power requirements	Continuous Venting – desirable, especially if combined with suit pressure relief

A variety of scrubber geometries and types were tested including (examples are shown in Figure 3):

- Spiral heat exchanger
- Flat plate heat exchanger
- Concentric tube heat exchanger
- Woven copper matrix (Choreboy pads)

Flat plate with vibrating motor  
 Flat plate with thumper  
 Flat plate with air knife  
 Choreboy with Nickel-chrome wire heater and high pressure gas

A MathCAD model was created to calculate consumables and power required for the scrubber to function. The model defines a number of constants (based on temperatures and pressures) such as density, specific heat, and heat of vaporization for oxygen, nitrogen and CO<sub>2</sub>. Inputs include ventilation gas flow rate, CO<sub>2</sub> injection, and suit and ambient pressures. This model was revised several times to incorporate better understanding of the process based on experimental results and to match the configurations of the developed concepts.

During testing, several spreadsheet-based models were also developed incorporating testing data. The most important of these was an iterative model used to predict CO<sub>2</sub> levels in the ventilation loop based on loop pressure changes, CO<sub>2</sub> and N<sub>2</sub> inputs and outlets, CO<sub>2</sub> storage in the scrubber, and loop volume. Models were based on actual data or assigned simulated values. This model was verified with data from multiple tests. It was used in calibrating the CO<sub>2</sub> sensor, exploring test results, and development of future work and concepts.

## BREADBOARD AND TESTBED DEVELOPMENT AND DESIGN

Based on the experimental feasibility studies and testing, we developed a breadboard concept with the following features:

Continuous operation during EVA. CO<sub>2</sub> is continuously being frozen out of the ventilation loop, knocked off the cold surfaces, and vented from the suit. This capability provides for high operability as there are no actions required to prepare, operate, regenerate, or recharge the scrubber.

Smooth freeze out surfaces allow for easier CO<sub>2</sub> removal with crew movement or air pulses. Momentary bypass of the scrubber may be required during air pulses. There are no moving parts to the scrubber, supporting high reliability and low maintenance requirements.

Fine mesh, cooled to cryogenic temperatures, prevents CO<sub>2</sub> snow particles from passing through scrubber back into ventilation loop.

CO<sub>2</sub> removed from the ventilation loop is sublimated back through the recuperator to recover the energy used to cool it, then vented overboard through the suit pressure relief system as warm gas. Battery power is not required to sublimate the CO<sub>2</sub> and warm material, and consumables are not required to re-cool the scrubber or recuperator. This minimizes power and consumables usage.

A PLSS schematic is shown in Figure 4 that illustrates how the cryogenic scrubber would be integrated into the PLSS.

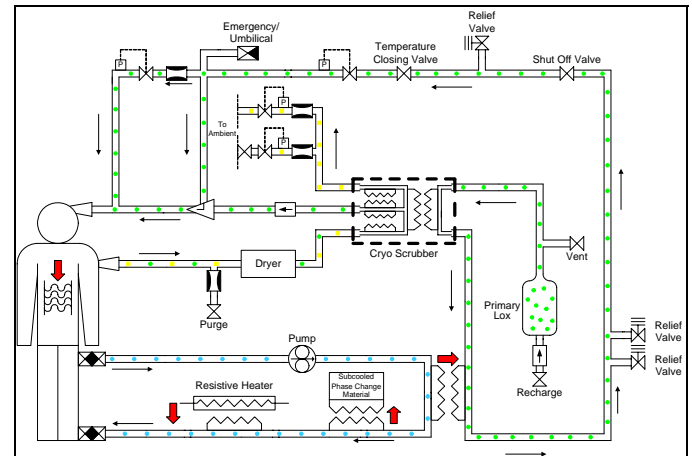


Figure 4: PLSS Schematic With Continuously Regenerating Cryogenic Scrubber

At the same time a schematic for a testbed was developed and requirements derived for the components and sensors. The testbed features:

N<sub>2</sub> and Liquid Nitrogen (LN<sub>2</sub>) used in place of Oxygen (O<sub>2</sub>) and LOX  
 Operation at pressures from 22 to 115 kPa  
 Free volume of ~ 70 L  
 Ventilation loop flow rates to 35 slpm at 29.6 kPa (100+ slpm at 101.3 kPa)  
 Variable dilution flow (N<sub>2</sub> input to simulate ejector use)  
 Controlled CO<sub>2</sub> injection up to the equivalent of 600W of metabolic production  
 Relief flow from ventilation loop or scrubber breadboard  
 Measurement and control of LN<sub>2</sub> flow to ~200 slpm  
 Data collection for up to 24 sensors. This testing used:

- 8 Thermocouples
- 2 Absolute pressure sensors
- 1 Delta pressure sensor
- 3 Flow sensors
- 1 Relative Humidity sensor
- 1 CO<sub>2</sub> injection control / sensor
- 1 CO<sub>2</sub> sensor (installable in two locations)

## CRITICAL FUNCTION AND PROOF OF CONCEPT TESTING

During this phase twenty-seven tests were completed, broken down into the following categories:

Testbed development tests – fourteen tests; testbed operations and performance, instrumentation checkout, software setup  
Recuperator tuning tests – four tests; performance of different recuperator layouts  
Breadboard development tests – four tests; breadboard operations, performance, procedure verification  
Nominal tests – five tests; 300 W average for one to five hours, metabolic profile for four hours

Additional nominal and optional testing was initially planned including longer durations, operations in additional orientations and simulated atmospheres. The performance of the breadboard during the testing rendered this additional testing moot, and it was not conducted.

## CONCEPT DEVELOPMENT

Two rounds of concept development occurred during the project. The first round, conducted in concert with the experimental feasibility studies, guided the development of the breadboard and provided a target for the modeling. While never completely realized, this concept took expected requirements such as heat transfer surfaces and flow rates and provided estimates of mass and volume.

The final round of concept development occurred after final testing and forms the basis of the recommendations presented in this report.

## TECHNOLOGY READINESS LEVEL ASSESSMENT

Future development plans and any limiting technologies and improvements required for a viable PLSS subsystem have been identified. An assessment of TRL level reached was conducted.

## CRYOGENIC SCRUBBER BREADBOARD OVERVIEW

### DESIGN GOALS

The cryogenic scrubber breadboard is a proof-of-concept. As such, the design goals incorporated features that would enable observation of its function and allow modifications to the design as we learned from experiments. Specific design goals included:

Modularity - The breadboard is modular, allowing components to be changed independently. The recuperator can be resized by adding or removing aluminum plates, or it can be removed entirely and replaced with a different size or style of recuperator. This was a lesson learned from a previous effort in which the recuperator was fixed in size and permanently part of the structure, and it could not be

changed when it became clear it was not functioning correctly. The scrubber portion of the breadboard can also be removed from the recuperator in order to make modifications or to replace it.

Accessibility - The breadboard was designed so internal components could be accessed relatively quickly. This allowed rapid exposure and observation of inner workings to assess performance or diagnose problems before all the CO<sub>2</sub> sublimated away. The breadboard could also be easily reassembled for the next test.

Cost Efficiency - The breadboard was designed with cost in mind. Flight size, weight, and pedigree was not required for this research and development effort. The components and materials were purchased from commercial vendors, machined in-house, and assembled.

Thermal Efficiency – Heat leak into the breadboard was minimized by using low conductivity materials and minimizing thermal mass. Structural plastics were used for the outer shell and inner plates separating components.

Sub-atmospheric Pressure Compatibility – Testing in a relevant environment included actual operating pressures of 29.6 kPa (4.3 psia). This eliminated complexities, potential errors, and unknown effects resulting from operating at higher pressures and compensating for, calculating, or estimating the differences.

## DETAILED DESIGN DESCRIPTION

The assembled cryogenic scrubber breadboard is shown in Figure 5. A cross section view of the breadboard with components labeled is shown in Figure 6. Ventilation loop connections interface with the breadboard at the bottom, where they enter or exit the recuperator and exchange heat with each other. Cryogen, air knife gas, and the instrumentation feed-through interface with the breadboard at the top where they penetrate directly into the scrubbing area.



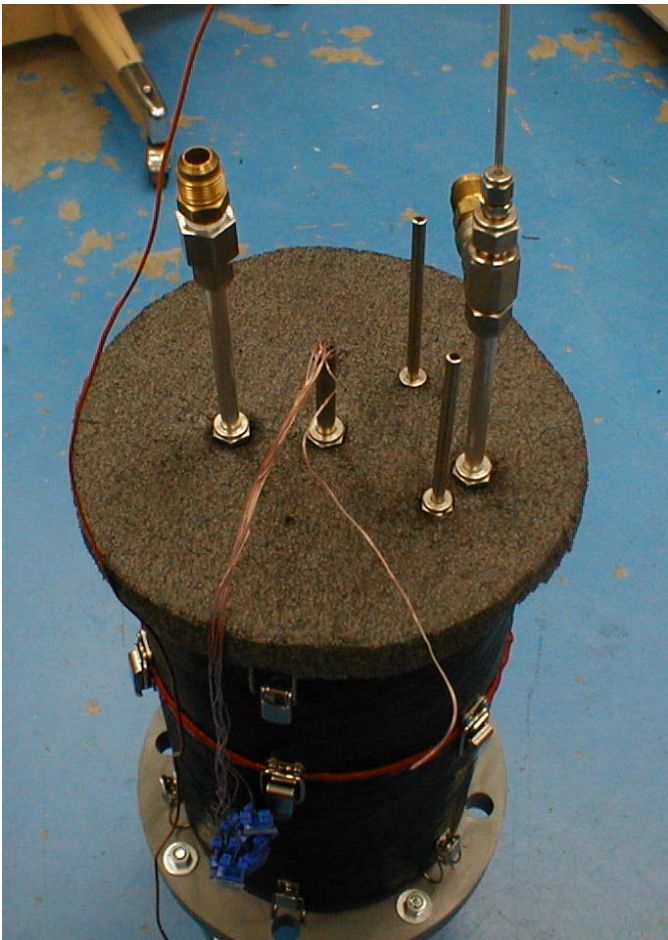


Figure 5: Assembled Cryogenic Scrubber Breadboard

towards the middle. CO<sub>2</sub> freezes out onto the surface of the heat exchanger and drops down to the flow distribution ring below it. Also visible in the photograph are the air knives. These are used to pulse air through the spiral and dislodge solid CO<sub>2</sub> from the heat exchanger. The air knives are tubing with thin slots facing each other. When pressurized air is applied to the air knives, it exits the slots in a stream to fracture and entrain solid CO<sub>2</sub>.

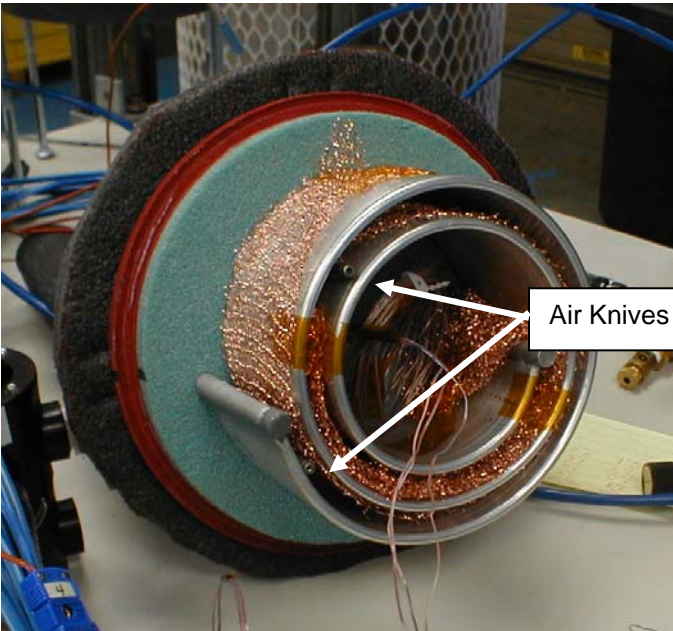


Figure 7: Cryogenic Heat Exchanger

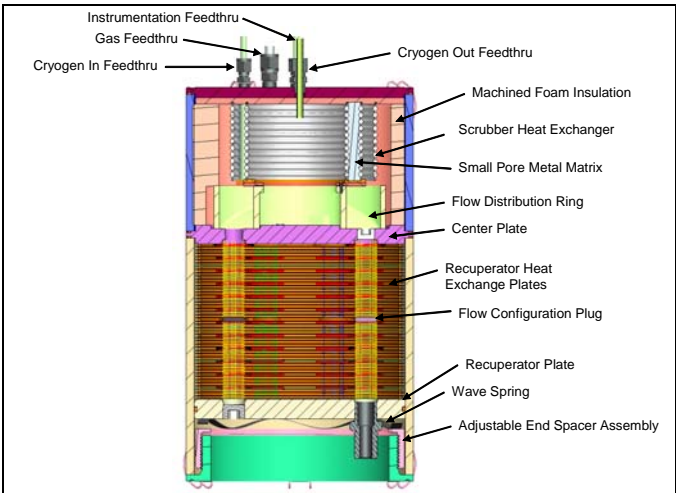


Figure 6: Breadboard Details

Figure 7 shows the spiral cryogenic heat exchanger. Cryogen flows through the inside of this aluminum extrusion while the ventilation gas flows over the outside

## DETAILED FLOW DESCRIPTION

CO<sub>2</sub> laden ventilation gas enters the recuperator at the bottom of the device (green in Section C-C of Figure 8). The gas flow spreads out across the recuperator heat exchange plates to the other green tube. In this area, the CO<sub>2</sub> laden ventilation gas exchanges heat with the cold, cleaned ventilation gas exiting the scrubber and with the CO<sub>2</sub> snow being ejected from the scrubber, each on a different circuit within the recuperator. The ventilation gas entering the freeze out portion of the device is now cooled as it flows around the spiral cryogenic heat exchanger towards the center of the breadboard. The gas flows through the flow distribution ring and over the cooling coils where CO<sub>2</sub> is frozen out. A small pore metal matrix behind the cooling coils allows the clean ventilation gas to pass through while preventing the CO<sub>2</sub> snow particles from continuing through the ventilation loop. The cold clean ventilation gas returns through the flow distribution ring and into the recuperator, cooling the incoming ventilation gas (Section A-A in Figure 8). The CO<sub>2</sub> builds up until it is jarred loose from the cryogen heat exchanger or blown

loose with an air impulse. It is sucked down through the flow distribution ring into the recuperator in the CO<sub>2</sub> concentrated gas circuit where it is sublimated, and vented out the suit pressure relieve device. The suit pressure relief device vents constantly for an ejector based ventilation loop, providing the driving suction to remove the CO<sub>2</sub>.

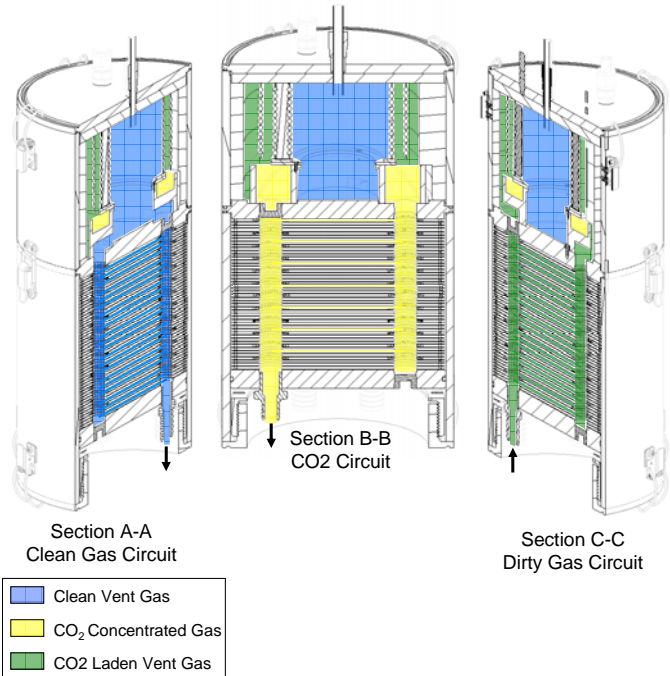


Figure 8: Flow Paths Through Breadboard

### VENTILATION LOOP TESTBED

The primary challenges in the development of a sub-atmospheric testbed were pressure control to the vacuum system and providing sufficient flow in the test loop. Instrumentation also proved to be somewhat of a challenge, as some instruments, in particular the CO<sub>2</sub> sensor, had very pressure-dependent behavior.

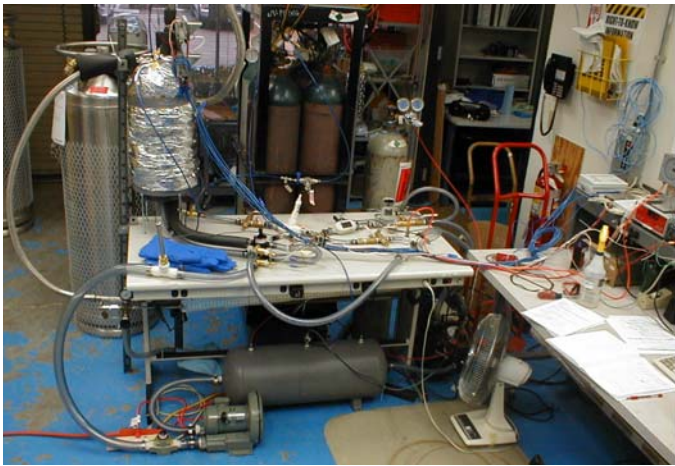


Figure 9: Testbed

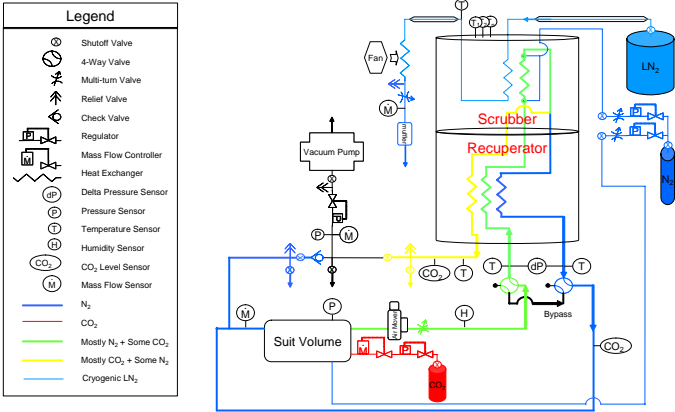


Figure 10: Testbed Schematic

The testbed was primarily constructed with generally available laboratory and industrial instrumentation and pressure components. All test operations were performed with written procedures to reduce sources of variability in the test results.

The pressure in the test loop was lowered below atmospheric conditions by a rotary–vane oil bath vacuum pump. While a dry type vacuum pump would have provided a better solution, no reasonably priced systems met the pumping requirements and potential for water vapor in the gas load. The ventilation loop pressure was controlled by a back pressure regulator. Feasibility testing and the initial setup for the testbed used a gas powered ejector type air mover. This provided adequate flow with high, but reasonable, gas consumption (and subsequent dilution of the ventilation loop gas) when used at near ambient conditions. At the ventilation loop operating pressure (29.6 kPa), maintaining the required ventilation loop flow (32.3 slpm or 4 acfm) required too much supply gas and diluted the



ventilation loop gas too much. After much research and testing, a modified ring compressor was used for the sub-atmospheric testing. A large diameter rising plug valve was also installed in the ventilation loop to vary the loop pressure drop and control flow rate.

Flow and CO<sub>2</sub> sensors in the required ranges were not available with calibration data for sub-atmospheric operation. The standard mass flow meters used in the OSS Cryogenics Lab, while not rated by the manufacturer, worked well at sub-atmospheric pressures. They were cross-checked against each other, other flow devices, and analytically with no discrepancies. The CO<sub>2</sub> sensor output was effected enormously by pressure. A correction curve was developed based on data from several special calibration tests. The ventilation loop volume was evacuated and then refilled with a known gas mixture. Multiple cycles and mixtures were run. This test data was used to produce a calibration curve for the sensor. The test data was also used to develop the predictive CO<sub>2</sub> model spreadsheet.

## RESULTS

The analytical models developed prior to testing of the breadboard assumed that there was no mixing of the flow through the scrubber. It was expected that all of the ventilation loop gas passing through the scrubber would be at (or very near) the saturation temperature of the LN<sub>2</sub> (~90K), freezing out essentially all of the CO<sub>2</sub> (the vapor pressure of CO<sub>2</sub> at ~90K is ~.0006 kPa). It was also assumed that no CO<sub>2</sub> would be stored in the scrubber and all of the separated CO<sub>2</sub> would be vented out the CO<sub>2</sub> out circuit, so that circuit would have a high CO<sub>2</sub> partial pressure. None of these assumptions turned out to be valid.

Test data showed much higher ventilation loop flow temperatures in the scrubber than expected. While still within performance limits, the CO<sub>2</sub> partial pressure out of the scrubber was much higher then expected, typically ranging from .5 kPa to .95 kPa. The CO<sub>2</sub> levels in the CO<sub>2</sub> out circuit were also in the same range (typically only 1 to 2 kPa). The scrubber was also storing substantial amounts of frozen CO<sub>2</sub>.

## ANALYTICAL MODELING

The models were modified during and after the testing to help explain these discrepancies.

The spreadsheet model of CO<sub>2</sub> performance was modified to account for storage of CO<sub>2</sub> (it already accounted for "imperfect" scrubbing), and then possible explanations for the observed behavior of the scrubber were evaluated. Modified versions of the model fit the data when it was assumed that some of the gas was effectively bypassing the scrubber (through internal leaks between the gas streams in the recuperator or scrubber). A bypass ratio of 40% showed similar CO<sub>2</sub>

partial pressures to the data results, as shown in Figure 10, combining a four hour metabolic profile and a four hour 300 W average.

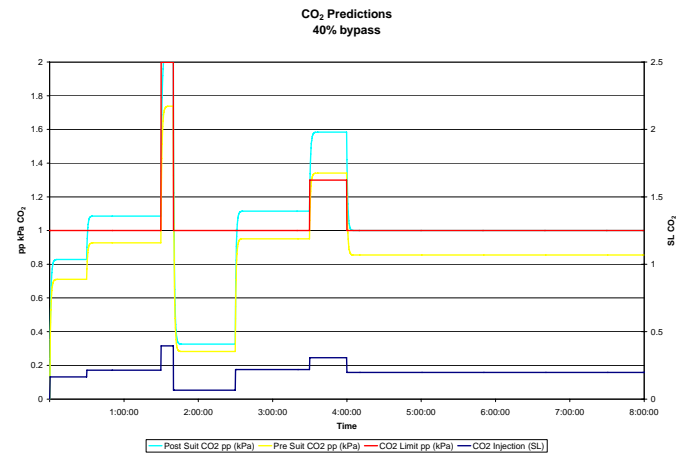


Figure 10: CO<sub>2</sub> Pressure Model (Excel) - 40 % Bypass

Larger than 40% bypass ratios increase the predicted CO<sub>2</sub> partial pressure over the limits. As discussed below, an intentional bypass of the scrubber and recuperator with no un-intentional internal bypass would improve performance of the scrubber.

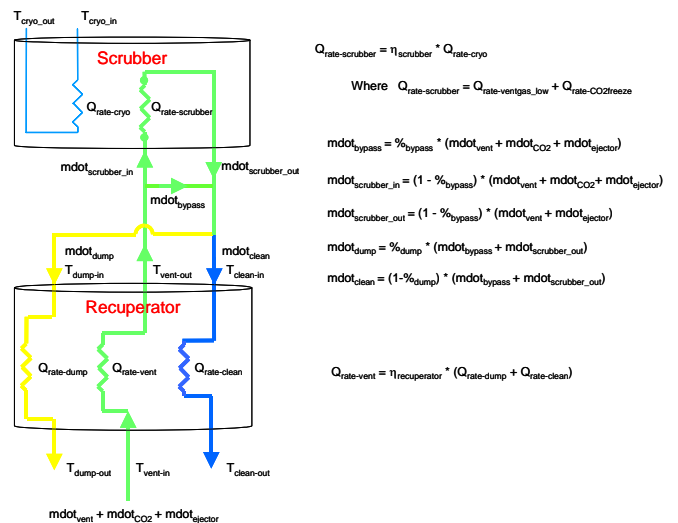


Figure 11: Scrubber Model Schematic with Bypass

The MathCAD model was modified to include an internal bypass, and the 40% bypass ratio developed with the spreadsheet was used in calculations. The temperature



assumptions used in the model were also modified to more closely match the actual test data. Figure 11 shows a schematic representation of the mass flows and heat transfers in the model.

With these modifications, modeled cryogen consumption related more closely to actual cryogen consumption (after corrections for pre-scrubber heat leak). Figure 12 presents these results.

	Prdctd Brdrd Model	Comparison of Feb 15, 2007 no bypass in model		Comparison of Feb 15, 2007 40% bypass in model		Comparison of Feb 14, 2007 40% bypass in model		Comparison of Feb 13, 2007 40% bypass in model		Comparison of Feb 12, 2007 40% bypass in model	
Input Variables	Model	Model	Test	Model	Test	Model	Test	Model	Test	Model	Test
Ventilation Loop Gas	Nitrogen										
Ventilation Loop Outlet Temp. (K)	305	300		300		300		298		300	
Ventilation Loop Inlet Temperature (K)	286	283		283		281		283		280	
Suit Operating Pressure (psi)	4.3	4.3		4.3		4.3		4.3		4.3	
Ventilation Loop Flow Rate (gm/min)	54.586	32.03		32.03		32.03		32.03		32.03	
Avg. Metabolic CO <sub>2</sub> Production (SLPM)	25 mg/sec	0.758	0.789	0.758	0.789	0.758	0.789	0.758	0.789	0.758	0.789
Ejector Flow Rate (SLPM)	.75 lb/hr	4.7	4.7	4.7	4.7	4.692	4.7	4.692	4.7	4.692	4.7
Test Loop Flow Rate (SLPM)	45.2	32.3	32.3	32.3	32.3	32.3	32.3	32.3	32.3	32.3	32.3
Scrubber Bypass Percentage	0%	0%		40%		40%		40%		40%	
Scrubber Heat Exchange Efficiency	0.9	0.9		0.9		0.9		0.9		0.9	
Scrubber Cycle Time (hr)	8	3		3		4		3		4.5	
Heat Sink Cryogen	LN2	LN2		LN2		LN2		LN2		LN2	
Cryogen Supply Pressure (psi)	22	22		22		22		22		22	
Dump Gas Temp out of Recuperator (K)	200	291		291		287		289		287	
Calculated Values	Model	Model	Test	Model	Test	Model	Test	Model	Test	Model	Test
Partial Pressure CO <sub>2</sub> (kPa)	0.518	0.883		0.883		0.883		0.883		0.883	
Cryogen Saturation Temperature (K)	81.417	81.42		81.42		81.42		81.42		81.42	
Cryogen Heat of Vaporization (kJ/kg)	194.64	194.6		194.6		194.6		194.6		194.6	
CO <sub>2</sub> Sublimation Temperature (K)	146.121	149.8		149.8		149.8		149.8		149.8	
Vent. Gas Temp out of Recuperator (K)	148.121	200		200		190		203		203	
Heat Sink Gas Outlet Temperature (K)	91.417	150		150		140		150		145	
Clean Gas Temp into Recuperator (K)	83.417	150		150		140		150		145	
Dump Gas Temp into Recuperator (K)	83.417	185		185		170		195		180	
Recuper. Heating (Cooling) Rates											
Ventilation Gas Cooling Rate (watt)	151.484	66.92		66.92		73.6		64.27		64.27	
Clean Gas Heating Rate (watt)	174.676	73.84		74.7		79.19		74.7		75.82	
Dump Gas Heating Rate (watt)	13.451	10		10.12		11.17		8.975		10.22	
Recuperator Heat Exchanger Efficiency	0.805	0.798		0.789		0.814		0.76		0.747	
Scrubber Heating (Cooling) Rates											
CO <sub>2</sub> Freeze-out Rate (watt)	14.825	14.83		8.895		8.895		8.895		8.895	
Ventilation Gas Cooling Rate (watt)	63.502	77.26		46.36		42.46		47.53		47.53	
Total Scrubber Cooling Rate (watt)	78.327	92.09		55.25		51.35		56.42		56.42	
Cryogen Heating Rate (watt)	87.03	102.3		61.39		57.06		62.69		62.69	
Cryogen Consumpt Rate (kg/min)	0.02536	0.023	0.01	0.014	0.01	0.013	0.008	0.014	0.008	0.014	0.008
Cryogen Consumpt Rate (SLPM)		19.7	8.5	11.82	8.5	11.43	6.5	12.07	6.5	12.31	6.5
Total Cryo Consumpt in 8 hours (kg)	12.2	11.0	4.7	6.6	4.7	6.4	3.6	6.7	3.6	6.9	3.6

Figure 12: Model Results Comparisons

## EXPERIMENTAL CRYO SCRUBBER BREADBOARD PERFORMANCE

Five breadboard nominal tests were conducted after the breadboard and testbed development and tuning tests were complete. During these tests we made some slight changes to the Cryogenic Scrubber configuration to improve or optimize its performance. The results discussed below are based on test data taken during the nominal tests.

The performance of the cryogenic scrubber breadboard can best be described as robust. Despite a number of drawbacks to the design, the cryogenic scrubber removed adequate quantities of CO<sub>2</sub> and proved to be relatively insensitive to internal leaks and impacts to the scrubber. Data from a nominal test of the cryogenic scrubber is shown in Figure 13 and is representative of data from all the nominal tests.

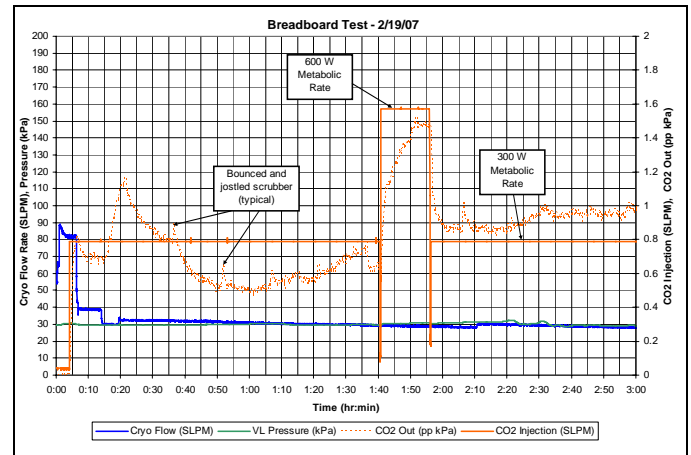


Figure 13: Typical Cryogenic Scrubber Performance Data

The CO<sub>2</sub> partial pressure limit for a 300 W metabolic rate is 1 kPa, and for a 600 W rate is 2 kPa. As shown in Figure 13, except for a brief excursion outside the limit shortly after start up, the cryogenic scrubber breadboard maintained the CO<sub>2</sub> levels within the required limits. The solid yellow line indicates the CO<sub>2</sub> injection rate (on the right axis) into the ventilation loop. The thin, dashed yellow line is the partial pressure of CO<sub>2</sub> in the ventilation gas exiting the breadboard (also on the right axis). For most of the test the CO<sub>2</sub> injection rate was .79 slpm, equivalent to 300 W metabolic rate. After rising to almost 1.2 kPa at the twenty-one minute mark shortly after starting the test, the ppCO<sub>2</sub> dropped for the next forty minutes reaching a minimum of .5 kPa. This dip, then subsequent rise in ppCO<sub>2</sub>, is apparent in most of the nominal tests. The initial rise may be due to the fact that the testbed was not yet completely chilled down. The ppCO<sub>2</sub> rise beginning at the 1:00 mark may be caused by CO<sub>2</sub> frost building up on the cold surfaces and insulating them. The surface of this frost would get warmer the thicker it built up.

The cryogenic scrubber was manually mechanically shocked and bounced several times at 15 minute intervals to simulate dynamic conditions on the user's back. The mechanical shocks were done with a fist on the side of the scrubber and the bouncing was done by lifting the device and dropping it about 1 inch. Corresponding small spikes in ppCO<sub>2</sub> of about .15 kPa can be seen in the graph at fifteen minute intervals starting at the twenty-one minute mark. These spikes are likely caused by CO<sub>2</sub> snow breaking loose near the exit of the scrubber and flowing out the clean gas stream into the recuperator where they sublime to gas. It is probable that much more CO<sub>2</sub> breaks loose in the scrubber, but it falls in the CO<sub>2</sub> vent out area or collects on vertical surfaces. It was anticipated that these spikes would be more significant, and that the scrubber would scrub more effectively after the loop stabilized. In general, it took the spike two or three minutes to stabilize and return to the same ppCO<sub>2</sub> level as before the bouncing.

The injection rate was increased to the 600 W metabolic rate for fifteen minutes at the 1:40 mark. The ppCO<sub>2</sub> increased sharply for ten minutes then leveled out at about 1.5 kPa for five minutes. When the CO<sub>2</sub> injection rate was returned to the 300 W metabolic rate, the ppCO<sub>2</sub> dropped immediately and returned to continue roughly on the same sloping increase as established before the 600 W metabolic rate interval.

Several configurations of the scrubber were tested in attempts to decrease CO<sub>2</sub> snow build up and increase heat transfer in the scrubber. In general, the features used to increase heat transfer (flow disrupters) made the scrubber perform better (lower ppCO<sub>2</sub>), but also held the CO<sub>2</sub> snow better which clogged the ventilation flow passages.

A test injecting CO<sub>2</sub> into the ventilation loop per the four hour metabolic profile (see Figure 14) was also conducted. The metabolic rates ranged from 100 W to 600 W. The test was terminated two hours and forty-five minutes into the metabolic profile when the ppCO<sub>2</sub> level exceeded the allowable limit and was continuing to rise. The spikes in ppCO<sub>2</sub> at fifteen minute intervals were caused by actuation of the air knives in attempts to dislodge solid CO<sub>2</sub> from the cold surfaces.

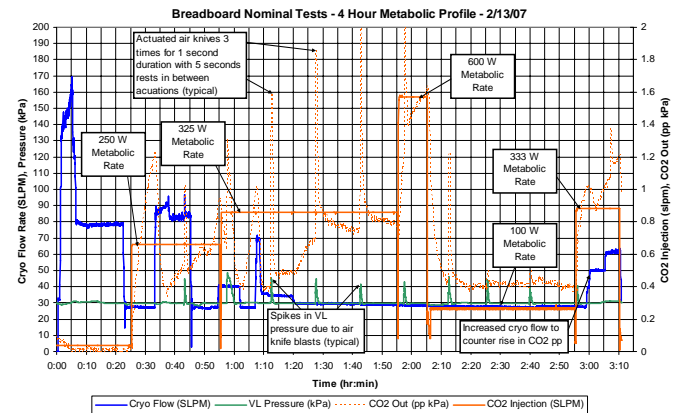


Figure 14: Cryogenic Scrubber Performance with CO<sub>2</sub> Injection per Metabolic Profile

A four hour test at the 300 W metabolic rate was performed (see Figure 15). The cryogenic scrubber maintained ppCO<sub>2</sub> levels below the required limit for the duration of the test. The spikes in ppCO<sub>2</sub> at fifteen minute intervals are due to operation of the air knives in attempts to dislodge solid CO<sub>2</sub> from the cold surfaces. Pressure drop through the recuperator and scrubber exceeded performance requirement limits and the capability of our sensor.

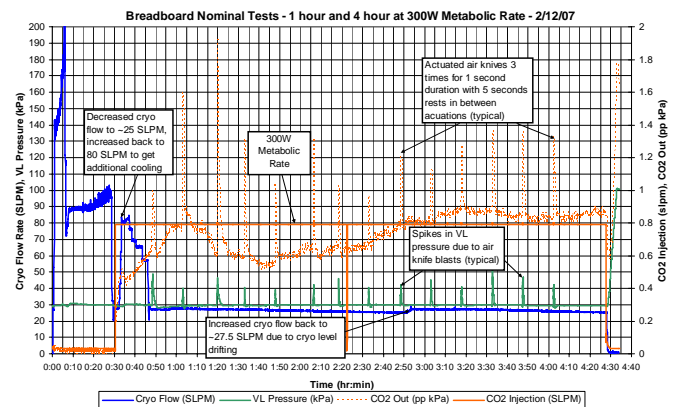


Figure 15: Cryogenic Scrubber Performance for Four Hour 300 W Metabolic Rate

The cryogenic scrubber consumed approximately 32 g/min of liquid nitrogen during operation. This greatly exceeds the theoretical cryogen consumption primarily due to heat leak into the system. We estimated the heat leak into the system by shutting off the ventilation loop flow and flowing just enough cryogen to keep the cryogenic heat exchanger at its operating temperature. The required cryogen flow was 24 g/min, indicating that 8 g/min of liquid nitrogen were being used for the basic operation of the cryogenic scrubber. Adjusting for liquid oxygen's 6% greater heat of vaporization, this translates

into a requirement for 3.6 kg of LOX for an eight hour EVA.

The pressure drop through the recuperator and scrubber ranged between 2.0 and 2.5 kPa. On average, the pressure drop increased about 0.3 kPa after several hours of operation. The majority of this pressure drop occurred in the recuperator due to the tuning done to the recuperator to recover the most cooling possible from the exiting gas. As the maximum pressure drop limit through the scrubber was 0.125 kPa, it is clear this area needs significant improvement. The recuperator was reconfigured to achieve its best possible heat exchange by having the longest, most torturous path possible. This comes at the cost of pressure drop. A recuperator with split folded fins would likely achieve better heat exchange efficiency with lower pressure drop. The 0.3 kPa increase in pressure drop during the test is due to the build up of solid CO<sub>2</sub> in the flow path. Ideally, the solid CO<sub>2</sub> would have sloughed off the cold surfaces, leaving the flow path clear and open. This was not the case. Observation of the cold surfaces after tests showed the solid CO<sub>2</sub> stuck to cold surfaces both loosely as a fluffy snow and solidly as hard ice (see Figure 16). The inability to easily remove solid snow is a fundamental problem with this concept.



Figure 16: Before and After Pictures of CO<sub>2</sub> Plugging Flow Passages

The cryogenic scrubber concept was based around the ability to continuously freeze out and remove CO<sub>2</sub> from the ventilation loop. The breadboard partially achieved continuous regeneration. CO<sub>2</sub> was being removed from the ventilation loop and the ventilation loop ppCO<sub>2</sub> remained within an acceptable range for several hours of use. Observation of the insides of the scrubber after a test showed solid CO<sub>2</sub> snow in the bottom of the freeze out portion of the scrubber where it falls into the flow venting overboard. Unfortunately, the solid CO<sub>2</sub> built up on the cold surfaces faster than it fell off, which led to choking of the ventilation loop and reduction in scrubbing performance.

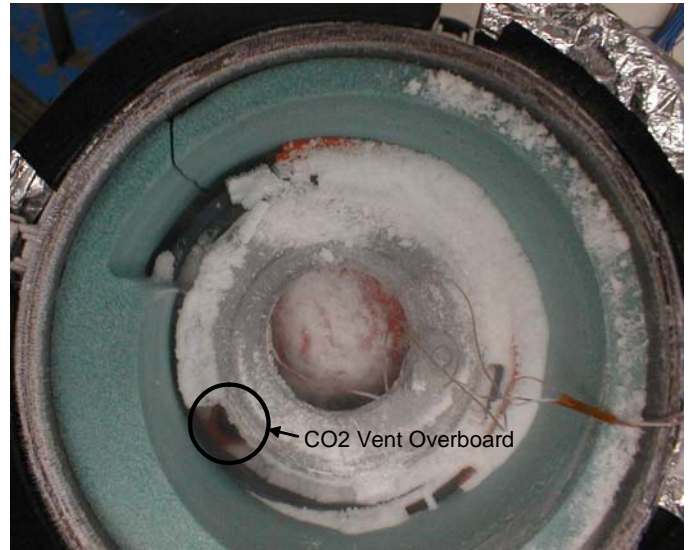


Figure 17: CO<sub>2</sub> Snow Visible On Ramps Leading to Overboard Vent

Several modifications were made to the scrubber to improve the release of snow from the cold surfaces. The initial configuration had smooth and bare aluminum exposed surfaces. Copper woven matrix was added to increase the heat transfer to the ventilation loop gas. This was successful, but also trapped more of the solid CO<sub>2</sub>. A coarse chicken wire with half inch square openings was used in place of the copper. This seemed to trap less CO<sub>2</sub>. Finally aluminum tape was added to the cold surfaces of the aluminum heat exchanger. The aluminum tape had a much smoother surface finish than the extruded heat exchanger and elsewhere in the cold area, the CO<sub>2</sub> snow seemed to slide more easily off of the tape's surface. None of these attempts eliminated the problem of CO<sub>2</sub> sticking to the heat exchanger.

## TRL ASSESSMENT

The cryogenic scrubber breadboard concept began as TRL 2, technology concept formulated. While the idea of freezing out CO<sub>2</sub> has been proven in past studies and in commercial applications, the concept of continuously regenerating by having solid snow drop off and sublimate out a ventilation port is new. A variety of experimental feasibility studies and testing (TRL 3) were performed with simplified systems to investigate ways to remove solid CO<sub>2</sub> from cold surfaces. TRL 5, "breadboard validation in relevant environment," was the goal of the project. The breadboard was tested in a relevant environment with correct ventilation loop absolute pressures and flows, and CO<sub>2</sub> injection rates. However, the breadboard was not validated; it did not succeed nor is there a clear or obvious way to overcome the difficulty of continuously removing the solid CO<sub>2</sub> from the cold surfaces.

## FINAL CONCEPT



A continuously regenerating cryogenic scrubber must overcome several hurdles to function properly in a PLSS:

- Improve solid CO<sub>2</sub> release from cold surfaces
- Operate in all orientations
- Improve recuperator heat exchange
- Improve cryogen heat exchange
- Receive high quality (100% liquid) cryogen

OSS believes that the first two hurdles are the most difficult, and it may not be possible to overcome them while maintaining the important guiding principles of simplicity, reliability, and operability. Based on the testing performed during this project, it is believed the best option for a cryogenic scrubber concept is to freeze and store the CO<sub>2</sub> for the duration of the EVA, rather than continuously regenerating it. This is the same approach taken in a previous project in which four hours worth of CO<sub>2</sub> was stored in a copper matrix. This approach retains the simple and reliable aspects of the process, but it requires increased operational overhead because it must be regenerated between uses. Similar to the breadboard tested, it would use no power, have no moving parts, and require no special consumables.

The freeze and store cryogenic scrubber concept is shown in a PLSS schematic in Figure 18. Specific differences between this concept and the tested breadboard include:

- A method of regenerating the scrubber is required. Adding heat to the insulated CO<sub>2</sub> storage area will sublimate the CO<sub>2</sub> away, and it can be vented out of the habitat or processed by the habitat's CO<sub>2</sub> removal system.
- A ventilation loop bypass around the scrubber allows less ventilation loop gas flow through the scrubber while still maintaining adequate CO<sub>2</sub> levels in the ventilation loop. Less gas flow through the scrubber will improve the cryogen consumption as there will be less losses due to recuperator inefficiencies. It will also allow the recuperator to be smaller or more efficient with less air flowing through it.
- The suit pressure relief occurs prior to the cryogenic scrubber so it vents CO<sub>2</sub> laden ventilation gas, making less work for the cryogenic scrubber. In an ejector based PLSS, this will reduce the amount of CO<sub>2</sub> that must be scrubbed and stored by 10 to 15%

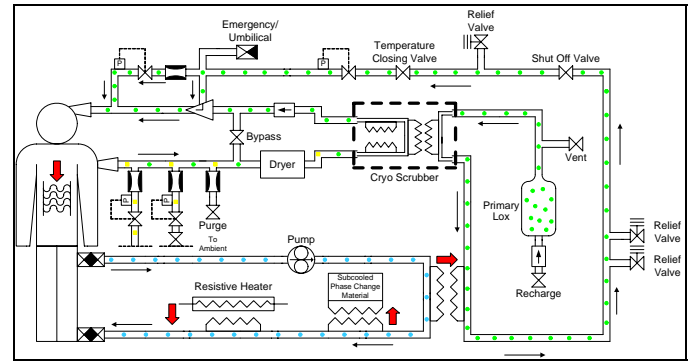


Figure 18: PLSS Schematic With Store CO<sub>2</sub> for Duration Cryogenic Scrubber

## RECOMMENDATIONS

Recommended follow-on efforts to this project include minor modifications to the cryogenic scrubber breadboard to optimize operations as a single bed scrubber with post EVA regeneration and further testing. Modifying and testing the breadboard as such would close out the “model – test – verify” loop for the recommended concept. It would provide a more complete data package for confident development of a cryogenic CO<sub>2</sub> scrubber if future NASA PLSS direction indicates CO<sub>2</sub> freeze out is a viable option. Further testing of the modified scrubber could be performed in a slightly modified version of the existing testbed.

The existing breadboard could be easily modified for operations as a single bed with post EVA regeneration (see Figure 19). Modifications would include:

- Recuperator layout modified for two-circuit operation, with the third circuit passing directly to the scrubber section exclusively for regeneration. This requires no new parts.

- Scrubber section modified with the following new parts-

- New cryogen heat exchanger similar to ones used in previous development work and proof of concept testing, aluminum tubing with copper matrix woven around the tubes. Uses existing cryogen ports.

- New flow distribution arrangement. Large diameter tubing (and a possible plate) would replace the flow distribution ring and seals.

- New annular insulation to fit around new configuration.

- Cryogen bath, or similar apparatus, on cryogen inlet to insure high quality (100% liquid) cryogen supply directly to the scrubber.

- Pressure taps to measure the pressure drop in the scrubber section, independent of the recuperator. These would use the air knife penetrations.



External adjustable bypass to minimize flow through scrubber while maintaining acceptable CO<sub>2</sub> levels in ventilation loop.

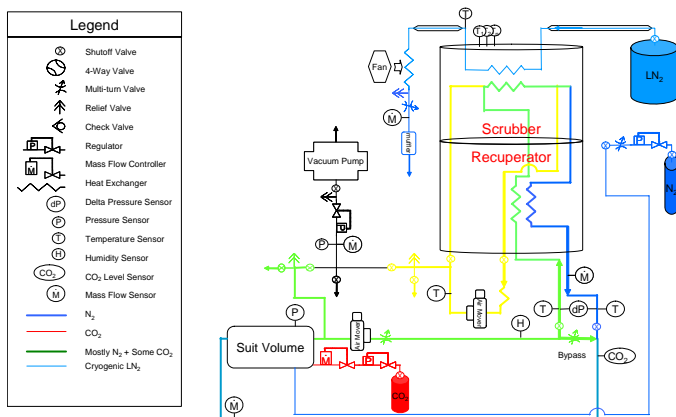


Figure 19: Modifications to Existing Breadboard and Testbed for Store and Hold Concept

## CONCLUSION

Oceaneering Space Systems and its teammate Raven Aerospace Technology developed and tested an innovative single-bed CO<sub>2</sub> scrubber breadboard with continuous regeneration based on freezing CO<sub>2</sub> out of a space suit ventilation loop.

The breadboard developed, based on Literature Investigation, Data Gathering, Experimental Feasibility Studies, and Initial Testing, met the design goals of:

- Modularity
- Accessibility
- Cost Efficiency
- Thermal Efficiency
- Sub-atmospheric Pressure Compatibility

During critical function and proof of concept testing twenty-seven sub-atmospheric tests were completed.

MathCAD and spreadsheet models were correlated to the test data and were used to make recommendations for further development.

While many of the initial performance assumptions were incorrect, the performance of the cryogenic scrubber breadboard was robust, removing adequate quantities of CO<sub>2</sub> with little sensitivity to internal leaks or impacts to the scrubber. The inability to easily remove solid snow from surfaces with sufficient heat exchange capability is a fundamental problem with this concept. Additionally, suit ventilation flows are too small to effectively vent released snow, even with optimal orientation in a earth gravity environment.

Based on the testing performed during this project, the best option for a cryogenic scrubber is to freeze and store the CO<sub>2</sub> for the duration of the EVA, rather than continuously regenerating it. Similar work, completed in 2002, successfully demonstrated storing four hour's worth of CO<sub>2</sub> in a chilled metal matrix and regenerating it after the four hours of scrubbing. This approach could be easily extended to an eight hour capacity and retains the simple and reliable aspects of the process, but it requires increased operational overhead because it must be regenerated between uses. Similar to the breadboard tested, it would use no power, have no moving parts, and require no special consumables.

## ACKNOWLEDGMENTS

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## REFERENCES

## CONTACT

## ADDITIONAL SOURCES

## DEFINITIONS, ACRONYMS, ABBREVIATIONS

## APPENDIX